AN UNUSUAL ABSORPTION FEATURE IN THE FAR ULTRAVIOLET SPECTRUM OF EARLY-TYPE SUPERGIANTS

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ABSTRACT

The OAO-2 satellite has been used to obtain far ultraviolet scans of six early-type supergiants. The data reveal the presence of a distinct, broad absorption feature centered near 1720 Å. This feature is unique in that it remains essentially constant in strength, breadth and central position over the spectral type range B0 I to A2 I. The feature also appears in the spectrum of the B-type shell star ζ Tauri, with a strength comparable to that observed for the supergiants. It appears weakly, or not at all, in the B and A main sequence spectra we have examined. The presence of the feature in spectra of supergiants and a shell star supports the hypothesis that it is an extended envelope phenomenon. We discuss in detail the hypothesis that the feature is due to a fortuitous blend of intrinsically strong lines arising primarily from the ground configurations of abundant metallic ions. An alternative possibility, that the feature results from the superposition of a "diffuse" band of undetermined origin upon the metallic line spectrum of the supergiants cannot be ruled out on the basis of the present data. Its remarkable constancy with spectral type may make the feature a useful indicator of early-type supergiants and shell stars in future programs involving narrow-band ultraviolet photometric observations of faint stars.

Apparent ultraviolet flux distributions for six early-type supergiants are plotted in Figure 1. Similar distributions for five main sequence stars and for the shell star ζ Tauri are given in Figure 2. Spectral types and luminosity classes are from the survey of Hiltner et al. (1969) or from Hoffleit (1964). All of the data were obtained with spectrometer 2 of OAO-2 (Code et al. 1970). The effective resolution of the instrument is 12 Å (B. D. Savage, private communication 1971); consecutive data points are obtained at increments of about 10 Å.

The spacecraft boresight tracker (BST) was used for the spectral scans of all six supergiants. It is thus reasonable to assume that the wavelength scale and zero point determined for one scan applies equally well to all. This is of particular importance in the case of the scan of α Cygni, for which a scale and zero point could not be determined unambiguously from identified spectral features. The validity of the adopted wavelength zero point for α Cygni was confirmed by BST scans of β Cephei, B2 III (not illustrated here), taken within eight orbits of the α Cygni observations.

We have used line identifications and observed wavelengths given by Morton et al. (1968) for ε Orionis to establish a mean relation between wavelength and grating orientation over the range 1170-1550 Å. A relation was established over the range 1486-1718 Å by use of prominent emission features identified in OAO-2 spectrometer 2 scans of the WN5 star HD 50896 now being studied by Lindsey F. Smith (private communication 1971). Here we utilized only subordinate lines, which, by analogy with subordinate lines observed in the visual, are unlikely to be red-shifted significantly from their laboratory wavelengths. The two relations were joined in their region of overlap and the resulting function was extrapolated smoothly from 1718 Å to about 1800 Å.

Numbered vertical lines in Figures 1 and 2 indicate twenty wavelengths near which prominent absorption features appear in one or more of the spectrum scans. Possible major contributors to these features are listed in Table 1. The multiplet numbers are from the Ultraviolet Multiplet Tables (Moore 1950, 1962, 1965). No attempt has been made to list the many lines of the second and third spectra of the metals which fall in the regions of interest. Such lines are probably present but better resolution than that available is required to show them.

The feature at position 3 in Figure 1 has been cross-hatched to facilitate identification. It appears as a well defined, pointed dip with a central flux which is about 0.80 of the flux in adjacent regions outside the feature. The apparent total width of the feature lies in the range 20-40 Å. We estimate the central wavelength to be 1720 Å. We believe it unlikely

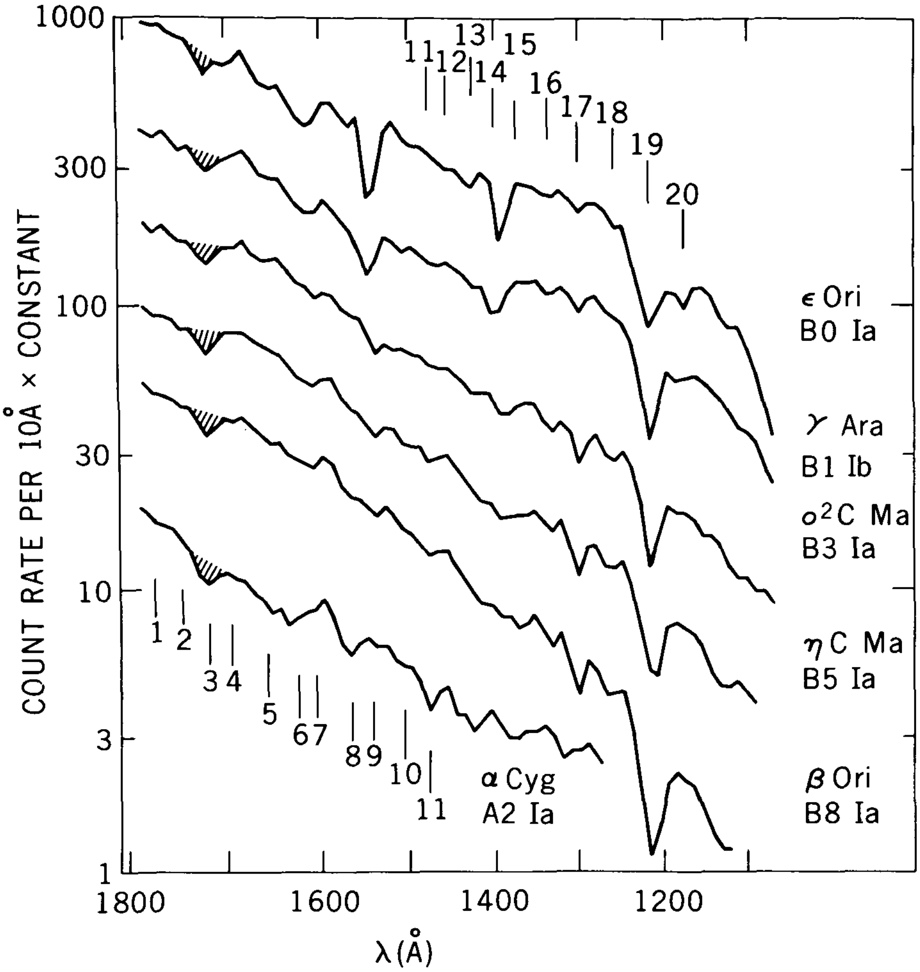

Figure 1.—Spectrum scans of six early-type supergiants. Count rates in a 10 Å band are multiplied by an arbitrary constant and plotted logarithmically vs. wavelength. Twenty positions near which prominent features occur are indicated (see Table 1). The cross-hatched feature near 1720 Å is discussed in the text.

that this estimate could be in error by more than ±7 Å; most of this uncertainty is systematic owing to our inability to specify increments less than one grating step. The constancy of the zero point is determined by the positional stability of the BST (about ±0.8 Å). The 1720 Å value derived here is in close agreement with the central wavelength of the feature, 1718 Å ± 4 Å, estimated by Code (private communication 1971) on the basis of an extended investigation of the dispersion curve for spectrometer 2.

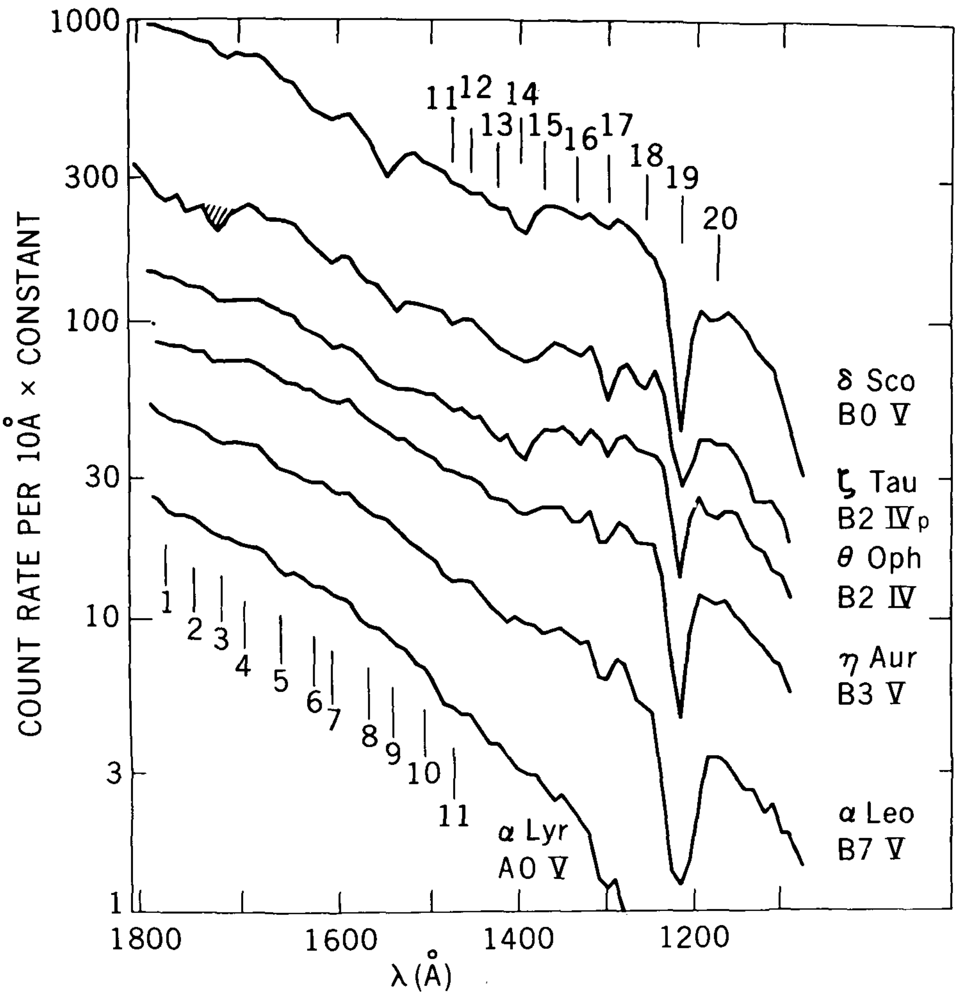

Figure 2.—Spectrum scans of five early-type main sequence stars and a shell star, ζ Tauri. Count rates in a 10 Å band are multiplied by an arbitrary constant and plotted logarithmically vs. wavelength. Twenty positions near which prominent features occur are indicated (see Table 1). The cross-hatched feature near 1720 Å in the scan of ζ Tauri is discussed in the text.

At 12 Å resolution one cannot distinguish between a simple broad absorption feature and a pattern of sharp features spread more or less symmetrically over the apparent line width. In accepting either possibility one must be prepared to explain the unique constancy of the feature in strength, breadth and central position over the spectral type range B0 I to A2 I. That the feature is indeed unique in this respect, within the

Table 1.

Possible Contributors to the Prominent Absorption Feature

Position	Position Wavelength (Å)	Possible Contributors	Multiplet	Wavelength (Å)
1	1773	S I	13	1782
		P I	1	1775-1788
		Ni II	3	1774
		* Sr II	4	1770,1778
		Al II	5	1764-1768
		Ni III	14,21,27,29	1761-1790
		C II	10	1760,1761
		* Zr III	2,3,11,12	1759-1783
2	1747	* Zr III	2,12	1754,1759
		N III	19	1748-1752
		N I	9	1743-1745
		Ni II	4,5	1742-1755
		Ni III	15,21	1741-1752
		Cr IV	13,14	1739-1750
3	1720	Mn II	13	1734-1738
		Cr IV	14	1731
		Si IV	10	1722-1727
		C II	14.02	1720-1722
		Al II	6	1719-1725
		N IV	7	1719
		Cr III	34	1712,1720
		Fe II	37,38,39	1710-1725
		Ni II	4	1710
		S I	10	1706,1707
		Si II	10,10.01	1705-1711
		Ni III	15,16,25,28,30,31	1702-1739
4	1697	S I	10	1706,1707
		Ni II	4,5	1703
		Cr III	34,71	1700
		Ni III	16,25,30	1688-1708
		Fe II	38,39,40,41	1686-1708
		P I	6	1686
		Ne II	7	1682,1688
5	1659	Si IV	27	1673
		P I	2	1672,1675
		Al II	2	1671
		A III	6	1670-1676

Table 1 (continued)

Position	Position Wavelength (Å)	Possible Contributors	Multiplet	Wavelength (Å)
5	1659	S I	11	1667
		C I	2	1656-1658
		Ni III	17	1650
		Fe II	40,41,42	1644-1671
		Ca II	1,5	1644-1652
6	1626	He II	12	1640
		Si IV	28	1635
		Ni III	17	1632
		Al II	9	1626
		Fe II	8,42,43,68	1622-1640
		* Zr III	29	1621-1638
		* Sr II	5	1620
7	1613	* Sr II	5	1613
		* Zr III	29	1612
		Fe II	8,43	1608-1618
		* Sc III	1	1598-1610
8	1568	Ca III	4	1563
		Si II	10.02,11	1562-1564
		A II	14	1560,1575
		C I	3	1560-1561
		Fe II	44,45,46	1559-1588
9	1542	Ca II	6	1554,1555
		Fe II	45	1550
		C IV	1	1548,1551
		Al II	10	1540
		* Ga II	5	1535
		P II	1	1533-1544
		Si II	2	1533
		Si IV	24	1533
		* Sr II	6	1531,1538
10	1508	Si II	11.01	1509-1512
		* Ga II	5	1505,1515
		P III	6	1502-1505
		Ni II	6,7	1500,1511
		Ti III	3	1499
		N I	4	1493,1495

Table 1 (continued)

Position	Position Wavelength (Å)	Possible Contributors	Multiplet	Wavelength (Å)
11	1478	* Sr II	7	1483,1489
		S I	3,4	1474-1487
		Si II	12,12.01, 12.02,15.04	1474-1485
		Ni II	6	1468
		Ti IV	3	1467,1469
12	1457	Ni II	7	1455
		Ti III	5	1455
		Ti IV	3	1452
		S I	12	1448
13	1426	Si II	13,13.01	1434-1439
		Ca II	7	1433-1434
		C I	65	1432-1433
		Si III	9	1417
		* Ga II	2	1414
		S I	5,6	1413-1437
		Fe II	47	1413-1425
		N I	10	1412
14	1399	Si II	13.02,13.03,14	1404-1410
		Si IV	1	1394,1403
		Cl I	1	1390-1397
		S I	6,7	1386-1413
		Mn II	14	1386
		Cr III	35	1384-1400
15	1372	S I	7	1382
		P III	7	1380-1382
		Mn II	14	1378-1383
		Ni II	8,9	1370-1381
		Si IV	19	1366-1369
		Cl I	1,2	1364-1380
		Mn III	8	1361-1372
		Cr III	35,36	1357-1384
16	1334	Ca II	2	1342
		Cl I	2	1336-1352
		P III	1	1335-1345
		C I	4	1329-1330
		Ti III	4	1328
		C II	1,11	1324-1336

Table 1 (concluded)

Position	Position Wavelength (Å)	Possible Contributors	Multiplet	Wavelength (Å)
16	1334	S I	8	1324,1327
		N I	11,12	1319-1328
17	1298	N I	13	1311
		Si II	3,13.04	1304-1310
		P II	2	1302-1311
		O I	2	1302-1306
		S I	9	1296-1306
		Si III	4,10	1295-1303
		Mn II	6	1291,1292
		Ti III	1,2	1286-1299
		Mn III	9	1284-1292
		Cr III	12,28,37	1280-1316
18	1256	Fe II	9	1261-1267
		C I	9	1261-1262
		S II	1	1251-1260
		Si II	4,8,13.05	1247-1265
		C III	9	1247
		Cr III	5,6,13,20	1245-1273
		N I	5	1243
19	1214	Mn III	3,5,6	1220-1229
		H I	1	1216
		He II	13	1215
		Fe II	70,71,72	1213-1221
		Si IV	16	1211
		Si III	2	1207
		N I	1	1200-1201
		Cr III	7,14,15	1197-1230
		S III	1	1190-1202
		Si II	5,8.01,8.02	1190-1229
		Mn II	3,15	1189-1201
		C I	10,11,12,13,14	1189-1194
20	1172	N III	20	1183-1185
		Mn III	4,7	1180-1193
		C III	4	1175-1176
		* Ga II	6	1168-1187
		N I	6,7	1164-1168
		Mn II	4	1162-1164

*We include lines of some elements of low abundance on the possibility that they may be particularly strengthened in absorption by non-LTE excitation conditions.

range of wavelengths covered by spectrometer 2, becomes evident when one carefully compares the spectra illustrated in Figures 1 and 2 point by point. We have attempted to document in a rough way the constancy with spectral type of the feature. In Table 2 the ratio of the count rate, corrected for dark current, at 1720 Å to that near the apparent edge of the feature at 1740 Å is listed for each supergiant and for ζ Tauri. We have also included data for the B0.5 I star κ Orionis, which is not illustrated in Figure 1. The adopted criterion of line strength is susceptible to various sources of uncertainty and should not be taken too literally. However, it does indicate that the relative flux at the center of the feature lies within ±0.03 of 0.80, i.e. that it is constant to within the uncertainty of the data, for all the stars except α Cygni. The statistical uncertainty in the data for α Cygni is larger than for any of the other stars considered. The greater than average value of the central depth of the 1720 Å feature in α Cygni may not be real.

Table 2.

Relative Central Flux of the 1720 Å Feature

Star	Count Rate at 1720 Å / Count Rate at 1740 Å
ε Ori	0.78
κ Ori	0.77
γ Ara	0.82
ζ Tau	0.82
o^2CMa	0.83
η CMa	0.81
β Ori	0.79
α Cyg	0.73

No feature of comparable strength occurs near 1720 Å in the scans of main sequence stars shown in Figure 2. Broad, shallow undulations do occur in the vicinity of 1720 Å, especially at the earlier spectral types. However, these are not so

constant in appearance or position as the feature observed at 1720 Å in supergiants (see also Figures 1 and 2 of Code and Bless 1970). The present data demonstrate once again how much stronger, in general, absorption lines are in supergiant spectra than in main sequence spectra. However, it is not obvious that the weak absorption features near 1720 Å in the main sequence spectra are also responsible for the feature observed at 1720 Å in the supergiant spectra. We note for example that the central minimum of the shallow feature near position 3 in the spectrum of the B0 V star δ Scorpii lies closer to 1710 Å than to 1720 Å, while the central minimum near position 3 in the spectrum of the B0 Ia star ε Orionis lies squarely at 1720 Å. Similarly, the central minimum near position 3 in the η Aur (B3 V) spectrum lies closer to 1730 Å than to 1720 Å.

It is noteworthy that an absorption feature does occur at 1720 Å in the spectrum of ζ Tauri (Figure 2) with a strength and breadth comparable to that observed in the supergiant spectra. It is well known that the shell spectrum of ζ Tauri at visual wavelengths resembles to some degree the spectrum of a B8 supergiant, although particle densities in the shell are probably lower than those prevailing in the extended supergiant atmosphere (see the discussion by Underhill 1966). This resemblance also applies to the ultraviolet spectrum of ζ Tauri as may be confirmed by comparing the ζ Tauri spectrum with that plotted for β Orionis in Figure 1. The appearance of the 1720 Å feature in supergiant spectra and in the spectrum of a B-type shell star argues strongly for the hypothesis that the 1720 Å feature is an extended envelope phenomenon, that it is formed at low particle densities in dilute radiation fields.

An alternative hypothesis, which cannot be entirely excluded on the basis of our data, is that the feature is of interstellar origin and is comparable to the diffuse interstellar bands observed at visual wavelengths. The most highly reddened star illustrated here is δ Scorpii, $E(B-V) = 0.18$. If the feature were correlated in a simple way with interstellar extinction, it should appear in great strength in the spectrum of this star. That this is not the case casts doubt on the hypothesis of interstellar origin.

With the low resolution data at hand we can only speculate about the species from which the 1720 Å feature arises. One possibility, which we currently favor, is that the feature is the product of a fortuitous blend of lines of the sort listed for position 3 in Table 1. For example, it is possible that the N IV and Si IV lines dominate the feature near B0. As one proceeds toward later spectral types the intrinsically strong lines arising from the ground configurations of Ni II and Ni III become dominant. The Ni III spectrum seems especially likely for stars such as ζ Tau, γ Ara, o^2 CMa and η CMa whose spectra also contain prominent absorption features near 1750 Å

and 1770 Å where other strong Ni III lines occur. At the late B and early A spectral types Ni II, Fe II, Al II, etc. may dominate. However, this explanation is not without difficulties. If Fe II plays a major role near 1720 Å, it should also produce a major feature near 1670 Å. This is apparently not the case for the stars observed here. Similar considerations apply to the lines of Al II, Cr III, Cr IV, S I and Si II which fall in the neighborhood of 1720 Å.

Smit (1969) has measured equivalent widths of blue-violet and red lines of C II, Si II and Fe II in ground-based spectra of β Orionis. We note the weakness of Si II 3862, 3856 and 3853 Å in his spectra. These lines should be much stronger than the lines near 1711 Å arising from the same level. The blue lines of Fe II at 4549 Å and 4233 Å are quite weak in β Orionis. It is unlikely that the Fe II lines in the range 1710-1725 Å would be significantly stronger. Finally all of the C II lines listed by Smit are very weak, including those at 6578 and 6583 Å. It is improbable that the subordinate C II lines of ultraviolet multiplet 14.02 could be present in strength.

Of all the species listed for position 3 in Table 1, the only one likely to be of great importance in a late B-type spectrum is Ni II, with possible contributions also from Ni III and Mn II. It is difficult to understand how these ions alone could preserve the observed symmetry of the feature. The dominant multiplet (16) of Ni III contains, for the most part, lines lying shortward of 1720 Å. The dominant line of Ni II in this region falls at 1710 Å. Only the Mn II lines fall longward of 1720 Å and they lie rather close to the red edge of the feature.

This discussion may be summarized by noting that a certain degree of implausibility must be attached to an hypothesis requiring that a feature which remains so constant in general appearance, strength and central wavelength over a wide range of spectral types should be composed of blended lines which individually are variable over that spectral type range. Not only must a sufficient number of lines from various ionization states be present but also the lines must each be capable of growing to great strength in an extended low density envelope. Moreover, such lines must maintain rigidly defined relative strengths, i.e. the strongest of the lines must lie closest to 1720 Å at all spectral types. It is possible that strong lines may exist within the interval 1700-1740 Å which have not been observed in laboratory spectra. Alternatively the 1720 Å feature may arise from a "diffuse band" of undetermined origin superposed upon the metallic line spectrum of the supergiants. We know of no autoionization lines which fall near this wavelength. We hope to investigate these alternatives in two ways: (1) by a detailed theoretical spectrum synthesis of the region

around 1720 Å and (2) by exploration of the region at higher resolution on future spacecraft missions or with rocket-borne spectrographs.

The great strength of the 1720 Å feature in supergiant and shell star spectra and its constancy over such a wide spectral type range makes it an ideal one-dimensional indicator of stars with extended atmospheres. For example, the ratio of the flux in the bandpass 1700-1740 Å to that in a nearby bandpass outside this range should serve to discriminate between early-type stars possessing extended envelopes and normal main sequence stars in narrow band ultraviolet photometric surveys. A second criterion would have to be found to discriminate between shell stars and supergiants.

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